International Journal of Mineral Processing 104-105 (2012) 53–57

Contents lists available at SciVerse ScienceDirect

International Journal of Mineral Processing

journal homepage: www.elsevier.com/locate/ijminpro

Settling velocities of particulate systems 18: Solid flux density determination by ultra-flocculation

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ARTICLE INFO

Article history:
Received 3 August 2011
Received in revised form 21 December 2011
Accepted 27 December 2011
Available online 5 January 2012

Keywords:
Thickening
Settling
Flocculation
Ultra-flocculation
Flocculant dosage

ABSTRACT

The scale-up of thickening parameters from laboratory to industrial plant is still an open problem. Several techniques have been in use but none is free of criticism. In order to clarify these issue, in this work flotation tailings from one of the major Chilean copper mines was subjected to flocculation-settling tests with Orifloc-2010 polycarylamide in a Couette type reactor. By varying the shear rate from 100 to 2000 [s^{-1}] the solid concentration from 1 to 15 [% by volume] and the flocculant dosage from 0 to 20 [g/ton] it was shown that an important interaction exists between these variables. At the optimal flocculant dosage, the optimal suspension concentration and the optimal flocculation time, an increase by 50% in the solid flux density function is possible when the shear rate of $\dot{\gamma} = 100[s^{-1}]$ is changed to the optimum value of around $\dot{\gamma} \approx 400[s^{-1}]$.

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1. Introduction

In many countries water has become a scarce commodity. The necessity of recovering and recycling water has turned thickening into an important process, requiring the best operational practice. This objective requires improvement in the control system that maximizes thickener underflow concentration, minimize flocculant consumption and, in general, permits the stabilization of the whole operation. Several feedback control systems have been proposed for thickening operations, unfortunately, due to the non-linearity of the process and to the slow response to perturbations, thickening is difficult to control and classical control systems fail to operate adequately. Even more importantly, current methods of thickener control are based on feedback to change operational variables that do not take into consideration the properties of the feed material. Two such parameters are the *solid flux-density* that expresses, for any concentration of a suspension, the product of the settling velocity and of the solid concentration (and, for a material of constant concentration, represents the momentum of the motion), and the *solid effective stress* that represents the compressibility of the sediment produced by settling. These parameters permit a phenomenological description of the thickening process. Models using these two parameters permit improved operation and optimal control strategies. Determination of these parameters is still an open problem (Bürger et al., 1999). In this paper we will discuss the determination of one of these parameters, the solid flux-density function.

Several techniques have been proposed to determine the settling velocity in laboratory experiments, the "jar tests" being the most common (Coe and Clevenger, 1916; Richardson and Zaki, 1954; Michael and Bolgers, 1962). The Jar test involves homogenization of suspensions varying solid concentrations in settling cylinders, introduction of the flocculant and mixing by moving a plunger up and down in the cylinders, or by inverting the cylinders several times. This procedure is claimed not to be satisfactory because of the local over-dosing that can occur when the relatively concentrated flocculant solution meets the slurry (Kitchener, 1978); but more important is that the agitation obtained by this method does not produce the optimum flocculation. Farrow and Swift (1996) show that jar test has three main inconvenient: (1) the flocculation efficiency, measured by the sedimentation results, depend strongly on the mixing method (numbers of inversions), (2) that the diameter of the cylinders have a significant effect on the settling rate, diminishing as the diameter of the cylinder increases and (3) the experimental reproducibility associated with the process is low, with standard errors of the mean from 8 to 12% for the settling velocity.

Flocculation is used to aggregate fine particle to maximize the solid flux-density, which is directly related to thickener capacity. Hogg et al. (1993) showed that the choice of a flocculant is determined by chemical factors such as the mineral composition and solution chemistry. But

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doi:10.1016/j.minpro.2011.12.007

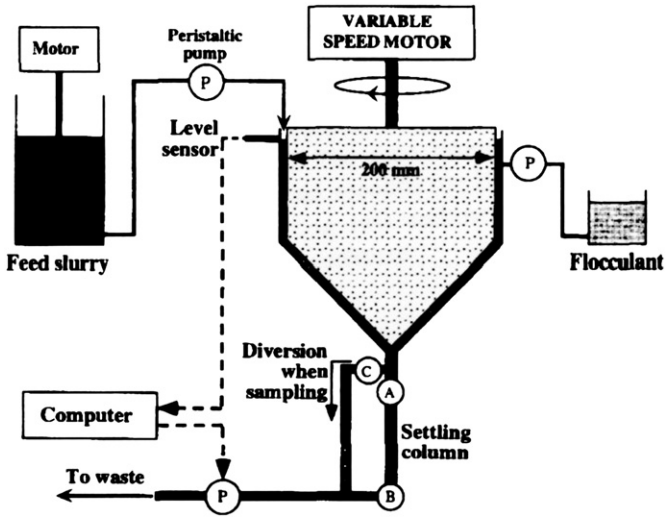

Fig. 1. Illustration of Farrow and Swift shear vessel (1996).

flocculant adsorption and bridging flocculation take place simultaneously and dynamic variables, such as the intensity of mixing and the mixing time, affect particle-particle linkages (Keys and Hogg;, 1979; Hogg, 1999). Molecular weight of typical flocculants fall in the range of 10–20 million Daltons. The transfer of the flocculant from the stock solution into the suspension and distribution within the dispersed system takes some time. An improved procedure to assess the efficiency of flocculation is via the use of a *shear vessel*, which is similar to a rotational Couette viscometers and has the advantage of quantifying the mixing quality through the shear rate. Several investigators have used the shear vessel in the past in coagulation experiments (Ives and Bhole, 1977; Smith and Kitchener, 1978; Stein et al., 1986) and in flocculation studies (Muhle and Domasch, 1991; Farrow and Swift, 1996; Rulyov, 1999, 2004; Rulyov et al., 2005a, 2005b; Rulyov et al., 2009).

Farrow and Swift (1996) designed their shear vessel with concentric cylinders of 200 and 210 [mm] in diameter and 120 [mm] in length (Fig. 1). At the bottom of the vessel a glass tube 14 mm in diameter and 220 [mm] in length was used to measure the settling velocity. The experiments were carried out at a constant rotational velocity of 200 [rpm]. The outflow of the shear vessel was introduced immediately in the settling column, depicted as A and B in the figure. The authors conclude that the combination of shear vessel and settling column overcame most of the problems associated with the jar test, in particular the strong dependence of batch settling test on mixing rate and cylinder diameter.

It was shown by Rulyov (1999) and Rulyov et al. (2000) that the mixing time in flocculation can be reduced down from minutes to 5–6 s by the appropriate hydrodynamic treatment of the suspension in a shear vessel at high shear rate $\dot{\gamma}$. This treatment, termed "ultra-flocculation" (Rulyov, 2004; Rulyov et al., 2005a, 2005b), ensures that, not only flocculant macro molecules are quickly and evenly distributed within the suspension and adsorb onto the surface of the particles, but also provides for the formation of large and dense flocs. Depending on the size distribution and density of the solid particles in the dispersion, as well as on their volume concentration, the optimum values of the mean shear rate $\dot{\gamma}$ may vary in a wide range such as $300<\dot{\gamma}<5000$ $[s^{-1}]$. The significant advantage of ultra-flocculation is that it ensures a good mix of small and large particles in flocs before they get into the settler, thus providing for fast sedimentation and high degree supernatant clarification (Rulyov et al., 2009). It was recently shown that under certain conditions intense agitation for short times may even change the nature of flocculation, from total flocculation to a selective flocculation of only some mineral constituents (Ding and Laskowski, 2007).

In this work an instrument called *UltraflocTester* has been used, which combines a shear vessel with variable shear rate and an optoelectronic device that measures the fluctuation via intensity of the a light beam passing normally through the transparent tube, while the formed flocs pass through this tube, to (1) analyze the relationship of flocculation efficiency (or mean flocs size) with solid concentration, flocculant dosage and shear rate, (2) the effect of the concentration and shear rate on the settling velocity and solid flux density and (3) the effect of the solid concentration on the optimum shear rate for flocculation.

2. Material, experimental set-up and method

Flotation tailings from one of the major copper flotation plants in Chile were used in all the experiments. Solid concentration was varied over the range from 1.8 to 15 [%] by volume] (4.7 and 32.3[%] by weight); material density was 2700 [kg/m^3]. An average particle size of ,$\bar{x}_{50} = 20[\mu m]$ with size distribution characterized by $\bar{x}_{80} = 40[\mu m]$ and $\bar{x}_{20} = 0.5[\mu m]$, was determined using a Sympatec Helos-Rhodos laser dispersion instrument. Orifloc-2020 polyacrylamide was used as a flocculant with a molecular weight of 9.64×10^6[g/mol].

The set-up to perform the ultra-flocculation tests is shown in Figs. 2 and 3. It consists of a small shear vessel, referred to as ultra-flocculator in Fig. 2. This Couette reactor, with a rotating cylinder of 28 [mm] in diameter and a gap of 1.5 [mm] was fed continuously with the suspension of tailings by a measuring peristaltic pump. Before entering the Couette reactor the pulp receives continuously a diluted flocculant solution, at a flow-rate to give a pre-determined dosage. After 6 s treatment at a pre-determined shear rate in the Couette reactor, the flocculated suspension is discharged from the ultra-flocculator through a 3 [mm] inner diameter transparent tube equipped with an opto-electronic sensor which registers the fluctuation of intensity of the light beam passing normally through the tube [in accordance with techniques proposed by Gregory and Nelson (1984)]. The electronic signal is processed and displayed in a three digital format, thus showing, in

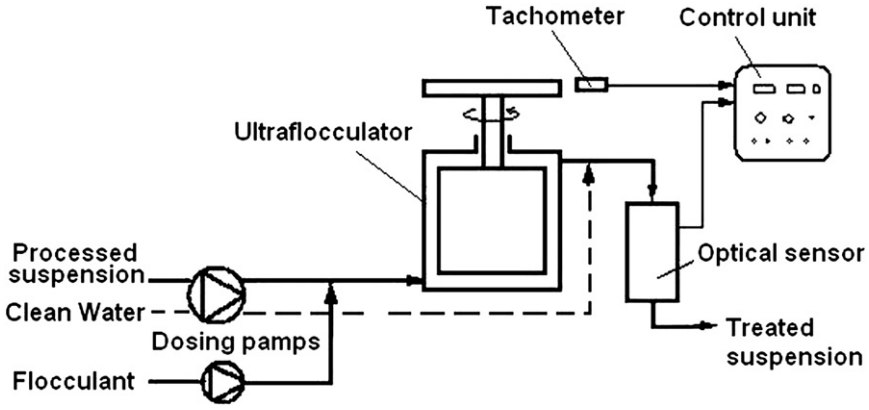

Fig. 2. Illustration of the UltraflocTester layout.

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